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Energy Procedia 27 (2012) 531 – 536
Energy Procedia

18.3 % efficiency on high ohmic emitters without selective emitters

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Abstract

Crystalline silicon solar cells with high ohmic emitters show higher efficiencies due to a better blue response. Unfortunately, the only way to contact them by screen printing is using the selective emitter technology. This study shows that contacting emitters with R_{sh} = 100 Ω/sq can be achieved by standard screen printing technology without selective emitter processing thanks to the development of a new silver paste. Thus, no additional process steps are needed to selectively dope the emitter. We study the electrical properties of industrially processed c-Si solar cells, with two different screen printing silver pastes (Pastes A and B) and emitters with sheet resistances R_{sh} = 80 Ω/sq, 100 Ω/sq, and laser doped selective emitter with R_{sh} = 20 Ω/sq on R_{sh} = 100 Ω/sq. On the solar cells with 80 Ω/sq emitter, paste B yields a low series resistance R_s = 0.72 Ω cm^2, thanks to its lower contact resistance ρ_c and its lower penetration into the space charge region, compared to paste A. The low series resistance leads to an efficiency gain $\Delta\eta$ = 0.7 $\%_{abs}$. We also obtain promising results on 100 Ω/sq, as the contact resistance $\rho_c \leq 3.1$ $m\Omega$cm^2 leads to a maximum fill factor FF = 78.8%. The efficiency η = 18.3 % of the 100 Ω/sq emitter solar cells is then comparable to the one of the selective emitter cells. With paste B, we demonstrate that it is now possible to contact high ohmic emitters, without the use of a selective emitter structure.

Keywords:
silicon solar cells, screen printing, high ohmic emitter

1. Introduction

The direct contact between silver (Ag) screen printing pastes and lowly doped emitters of crystalline silicon solar cells is hard to achieve because these emitters are so thin that they are easily shunted by the Ag paste [1, 2]. Within the last few years, this issue was solved by "selective" emitter [3]. However, this technology introduces further steps in the process fabrication. One of the challenges of the PV industry is thus to develop screen printing pastes which would be able to contact high ohmic emitters [4].

This study presents a new commercially available paste (paste B), which shows the ability to contact high ohmic emitters without selective emitter technology. We compare paste B to a standard paste (paste A)

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doi:10.1016/j.egypro.2012.07.105

on conventionally diffused emitters with R_{sh} = 80 Ω/sq, 100 Ω/sq as well as on selective emitter (SE) solar cells. From the current/voltage characteristic, internal quantum efficiency IQE, contact resistance ρ_c and 3D finger profile measurements, we conclude on the contacting behavior of these two pastes.

2. Experimental

Solar cells are fabricated on p-type, texturized 6" Czochralski (Cz) wafers with a thickness d_{cell} = 200 μm and a resistivity ρ = 2 to 4 Ωcm, . After RCA cleaning, high temperature $POCl_3$ diffusion with different diffusion parameters yields emitters with R_{sh} = 80 Ω/sq and R_{sh} = 100 Ω/sq sheet resistances. Some wafers with R_{sh} = 100 Ω/sq get laser doped selective emitter using a Nd:YAG laser with λ = 532 nm, using our patented doping process [5]. The width of the laser area is about 2.5 times larger than the finger width. After removing the phosphosilicate glass, a 80 nm thick PECVD-SiNx passivates the front surface of the wafers. After screen printing the full area aluminium on the back side, we use two different Ag screen printing pastes (pastes A and B). For each type of cells, we optimize the firing profiles by varying the peak temperature and the velocity. Finally, the cells undergo laser edge isolation. The solar cells characterization includes light and dark current/voltage characteristics, quantum efficiency, contact resistance, line resistance and 3D laser microscope measurements.

3. Results

Table 1 shows the in-house mean results (out of 3 to 4 cells) for the three different types of cells with R_{sh} = 80 Ω/sq, selective emitter and R_{sh} = 100 Ω/sq. The best cell results calibrated at ISECalLab is shown for the cell with R_{sh} = 100 Ω/sq.

Table 1. Mean electrical parameters from light and dark J/V-measurements of five types of solar cells. Cells have different emitters with R_{sh} = 80 Ω/sq, 100 Ω/sq, and selective emitter with R_{sh} = 20 Ω/sq on R_{sh} = 100 Ω/sq and front grids with pastes A and B. The contact resistance ρ_c, leakage current J_{02} and line resistance R_{line} are measured on one cell only.

Paste	R_{sh} [Ω/sq]	V_{oc} [mV]	J_{sc} [mAcm^2]	FF [%]	η [%]	R_s [Ωcm^2]	ρ_c [mΩcm^2]	J_{02} [nA/cm^2]	R_{line} [Ω/cm]
A	80	624	36.8	76.3	17.5 ± 0.2	0.83	4.1	177	0.19
B	80	629	36.8	78.4	18.2 ± 0.1	0.74	2.8	48	0.14
A	100-SE	635	36.8	77.8	18.2 ± 0.1	0.85	4.8	35	0.19
B	100-SE	633	36.7	78.4	18.2 ± 0.0	0.73	4.0	90	0.16
B	100	629	37.1	77.9	18.2 ± 0.1	0.76	3.1	216	0.12
B	100*	628.5	37.0	78.8	18.3				

*Best cell for solar cells with R_{sh} = 100 Ω/sq calibrated at ISE CalLab.

Concerning the solar cells with R_{sh} = 80 Ω/sq emitter, the paste B leads to an efficiency increase $\Delta\eta$ = 0.7 %, while the selective emitter cells with the pastes A and B have equal η. The paste B is also tested on an emitter with R_{sh} = 100 Ω/sq, leading to η = 18.3 %, equal to the one of the selective emitter solar cells.

In this work, we first compare the two pastes, using the solar cells results with R_{sh} = 80 Ω/sq, in order to understand the mechanisms which induce the gain in efficiency with paste B. As the solar cells with R_{sh} = 100 Ω/sq, both homogeneous and selective, give the same efficiencies, we study more in detail the solar cells results.

3.1. Two different silver pastes on cells with R_{sh} = 80 Ω/sq emitter

The increase in η for the cells with R_{sh} = 80 Ω/sq is mainly due to a higher fill factor FF and higher open circuit voltage V_{oc}. The decrease in contact resistance ρ_c and line resistance R_l, causes a decrease in series resistance R_s, thus an increase in FF, when the paste B is applied (Table 1).

In order to understand the effect of the pastes A and B on the series resistance, the different series resistance components are extracted using the method of Meier [6] for the solar cells with R_{sh} = 80 Ω/sq. This method does not include the contact resistance between aluminum and silicon on the back side.

Figure 1 shows the series resistance components obtained from the electrical measured data (contact resistance ρ_c, emitter sheet resistance R_{sh}, the line resistance R_{line}, wafer bulk resistivity ρ and aluminum sheet resistance $R_{sh,Al}$) and from the geometrical measured data (finger cross section σ_f, bus bar cross section σ_{bb}, finger width w_f, bus bar width w_{bb}, finger height h_f, bus bar height h_{bb}, cell area A).

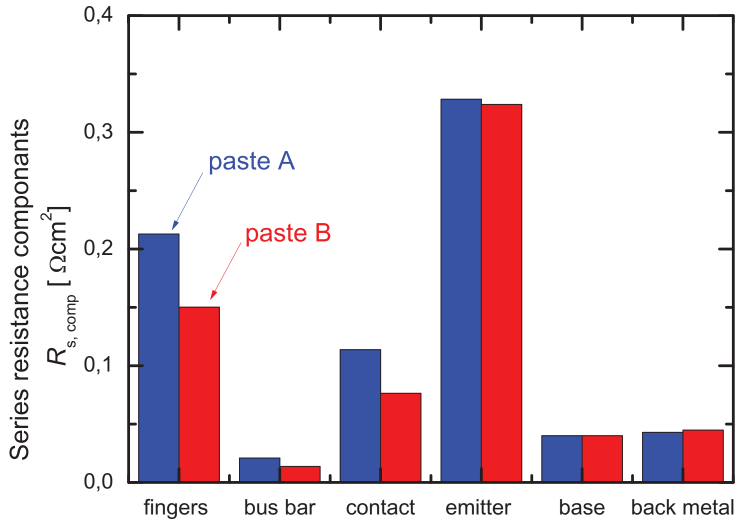

Fig. 1. Series resistance components calculated from measured data of the contact resistance, the emitter sheet resistance, the line resistance, the finger and bus bar area, the bulk resistivity and the aluminum sheet resistance for paste A and B, screen printed on solar cells with R_{sh} = 80 Ω/sq.

While the bus bar, base and back side resistances have a minor effect on the total series resistance, the series resistance is mainly influenced by the emitter, the finger and the contact resistances. The emitter resistance represents the highest contribution for both pastes, as the high ohmic resistance of the emitter, here 80 Ω/sq, hinders the lateral conductivity.

The two other main components, i.e. the finger and contact resistances, differ depending on the paste. With the use of the paste B, the contact resistance is reduced by 33% and the finger resistance decreases by 29%, compared to paste A.

The contact resistance diminution is explained by the study of the microscopic behavior of the paste, at the interface between the paste and the emitter, presented in [7].

Two factors influence the finger resistance: the resistivity of the paste and the cross section of the finger. As depicted in Fig.2, the finger shape of the two pastes differs. The paste B achieves a "square like" finger cross section, with an increased height, while the paste A shows a "hill like" cross section with a lower height. The metal resistivities ρ_m are $\rho_{m,A}$ = 3.3 μΩcm for paste A and $\rho_{m,B}$ = 3.1 μΩcm for paste B.

In order to determine which factor, paste resistivity or cross section, has more influence on the decrease of the finger resistivity, we calculate the finger resistance in different ways, as depticted in table 2. The 3D laser microscope measures the finger height h_f, width w_f and cross section σ_f.

The slight decrease of the metal resistivity ρ_m with paste B has a low influence on the decrease of the finger resistance. The main influencing parameter is the larger cross section of the fingers obtained with

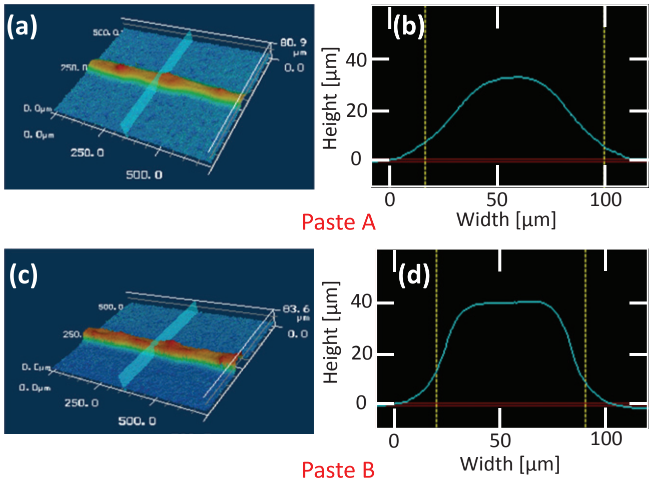

Fig. 2. 3D laser microscope pictures of fired fingers screen printed with (a) paste A and (c) paste B. Also depicted is the mean section of the fingers for (b) paste A and (d) paste B. Fingers of paste A have a "hill" like shape with a maximum height h_m = 32 μm. Fingers of paste B have a "square" like shape with a maximum height h_m = 41 μm.

Table 2. Influence of the finger cross section σ_f and metal resistivity ρ_m on the finger series resistance $R_{s,finger}$, depending on the use of paste A or paste B. The use of the finger cross section of paste B, which is larger than the one of paste A, shows a major influence on $R_{s,finger}$.

σ_f printed with	ρ_m of	$R_{s,finger}$ [Ωcm^2]
paste A	paste A	0.21
paste A	paste B	0.20
paste B	paste A	0.16

paste B after the printing and firing.

Table 1 also shows a gain in V_{oc} with paste B. As the emitter, bulk and back side are the same for all the cells, this gain is due to the use of the different pastes. Dark current/voltage curves were measured in order to extract the leakage current J_{02}. The leakage current gives information on the recombination activity taking place in the space charge region, i.e. on the incorporation of metal impurities into the space charge region [1]. The lower J_{02} observed for the cells with paste B proves that paste B has a lower penetration in the bulk emitter, thus decreasing the metal contamination of the space charge region.

3.2. Selective and homogeneous emitters solar cells with R_{sh} = 100 Ω/sq emitter

Table 1 shows that the selective emitter solar cells have similar electrical parameters for both pastes. In this case, the laser doped emitter under the metallization has a higher depth compared to diffused emitters with shallower depth (Fig. 3). The deeper profile yields lower J_{02} values because the emitter is less sensitive to the incorporation of impurities in the space charge region. Moreover, as the emitter is deeper, no difference is observed between the two pastes.

The benefits of a selective emitter with a highly doped region under the fingers are minimized with the use of paste B: the efficiencies are equal, with or without selective doping on the 100 Ω/sq emitters. As already discussed in the previous section, paste B is less agressive; it does not penetrate deep in the bulk emitter. On the one hand, the low contact resistivity ρ_c = 3.1 $m\Omega$cm^2 obtained on the shallow emitter

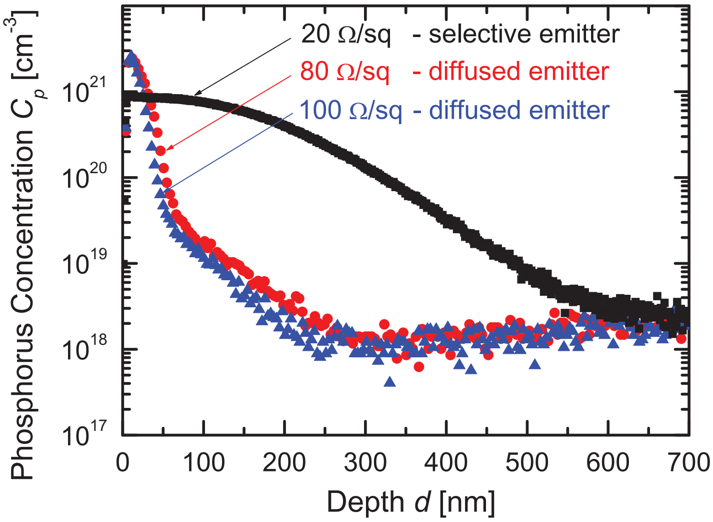

Fig. 3. Secondary Ion Mass Spectroscopy profile of the phosphorus concentration in the diffused emitters with R_{sh} = 80 Ω/sq, R_{sh} = 100 Ω/sq and for selective emitter with R_{sh} = 20 Ω/sq from the diffused emitter with R_{sh} = 100 Ω/sq. Selective emitter shows a higher depth and a lower phosphorus surface concentration compared to diffused emitters.

with R_{sh} = 100 Ω/sq is mainly influenced by the phosphorus surface doping C_p, which is still high, with $C_p > 2.10^{21}$ cm^{-3}. On the other hand, the contact resistivity measured on the selective emitter is higher, as the surface concentration decreases after the laser doping (Fig. 3).

Despite the gain in contact resistivity, the fill factor of the homogeneous emitter is lower than the selective emitter. This fact is due to the reduced lateral conductivity and to the higher leakage current J_{02} observed on the homogeneous emitter, as shown in table 1.

Finally, we notice that the lower FF is compensated by a better blue response for the homogeneous 100 Ω/sq emitter. Figure 4 shows the internal quantum efficiency IQE for the three types of cells with R_{sh} = 80 Ω/sq, selective emitter, and R_{sh} = 100 Ω/sq. During the external quantum efficiency measurement, the spot area was larger than the distance between the two fingers, i.e including the laser doped region of the selective emitter. As the difference between the selective and homogeneous emitters is the laser doped region (which is 2.5 times larger than the finger width), one can conclude that the laser doped areas next to the contact fingers influence the recombination in the blue region. Thus, the short circuit current density J_{sc} of cells with R_{sh} = 100 Ω/sq increases compared to the selective emitter cells (Table 1).

4. Conclusion

We compare two different commercially available pastes in order to contact high ohmic emitters. Thanks to better contact and line resistances, the fill factor increases of $\Delta FF = 2.1$ % in the case of the 80 Ω/sq emitter. Moreover, as paste B is less agressive, it penetrates less into the depth of the emitter. This fact avoids the need of a selective emitter, whose depth protects the space charge region from the metal contamination.

We obtain a maximum efficiency $\eta = 18.3\%$ on R_{sh} = 100 Ω/sq emitter solar cell, which is, up to now, the highest reported value on large area solar cells with shallow doped emitter, without selective emitter. The use of the new paste avoids the additional processing step of selective emitters for 100 Ω/sq emitters. A detailed study of the microscopic behaviour of the paste B is also presented in this conference [7].

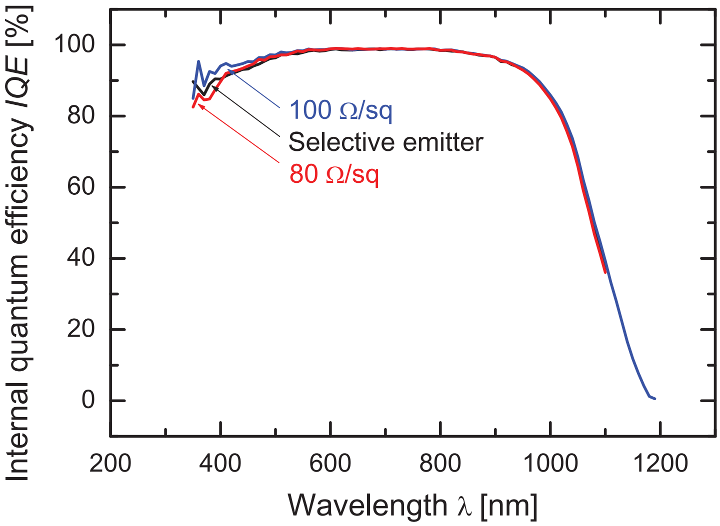

Fig. 4. Internal quantum efficiency *IQE* of the solar cells with homogeneous emitters with R_{sh} = 80 Ω/sq, R_{sh} = 100 Ω/sq and with selective emitter with R_{sh} = 20 Ω/sq on R_{sh} = 100 Ω/sq. All cells were screen printed with paste B. At wavelengths 350 nm $< \lambda <$ 450 nm, IQE increases with higher sheet resistances R_{sh}, even without the use of the selective emitter technology.

Acknowledgements

The authors gratefully acknowledge the technical work of M. Schneider, B. Winter, M. Saueressig and A. Bertram.

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